Modeling Emissions from Supernovae: Preparation for the Joint Dark Energy Mission

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Supernovae play an important role across a wide range of fields in physics and astronomy—they mark the endpoint in the life of stars but are an important source of energy to galaxies and play a role in the formation of new stars. They are produced in the formation of stellar-massed compact objects and, possibly, the seeds of the most massive black holes in the universe. They produce the bulk of the heavy elements in the universe and are the foundations of nuclear astrophysics. Finally, they require many of the same broad numerical and physics expertise in which LANL scientists have excelled, placing LANL in an ideal position to model these objects.

The importance of supernovae has become even more critical with the realization that type Ia supernovae can be used as distance estimators based on the fact that their peak luminosity can be calibrated and determined from the time-dependent behavior of these supernovae, allowing the discovery of dark energy. This discovery has marked one of the major scientific discoveries of the past decade and has galvanized the scientific community to use supernovae to do more than discover—to characterize dark energy using supernovae. Many new supernova search projects have grown out of this exciting result, immensely increasing the data we have on supernovae. Both NSF (Large Synoptic Survey Telescope - LSST) and NASA/DOE (Joint Dark Energy Mission - JDEM) are sponsoring major missions to study supernovae, representing a multibillion-dollar U.S. scientific effort.

The expertise at LANL in numerical hydrodynamics, radiation transport, atomic opacities, and nuclear physics, both theoretical and experimental, provides an ideal opportunity for LANL to make major contributions to the study of supernovae. In this report, we present LANL's successes over the past year in this effort, including the first-ever spectra from radiation-hydrodynamics calculations of supernovae.

The bulk of what we know about supernovae is derived from photon observations from the infrared through the ultraviolet wavebands. Hundreds of supernovae are observed in these wavebands and, with the planned LSST and JDEM missions, this number will rise to 100,000! For the next few decades, the spectra and time-dependent light curves will dominate the data we have from supernovae. Unfortunately, it is very difficult to tie the actual explosion and exact yields to the emission in these wavebands. The explosion produces both radioactive elements (principally ^{56}Ni) and strong shocks, both of which contribute to the radiation observed in these bands. But, especially in the case of radioactive elements, this contribution arises along a very indirect path: ^{56}Ni decays, emitting γ-rays that are then reprocessed into the

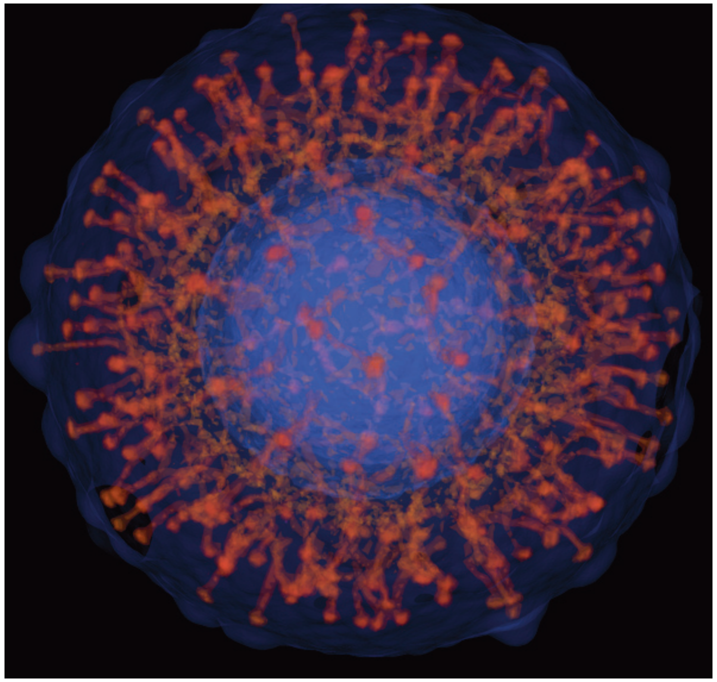

Fig. 1. Explosion of a massive star, color coded by temperature using the SNSPH code [3]. Rayleigh-Taylor and Richtmeyer-Meshkov instabilities drive mixing in the star. Understanding this mixing is important both for nucleosynthetic yields and calculating the emission from supernovae.

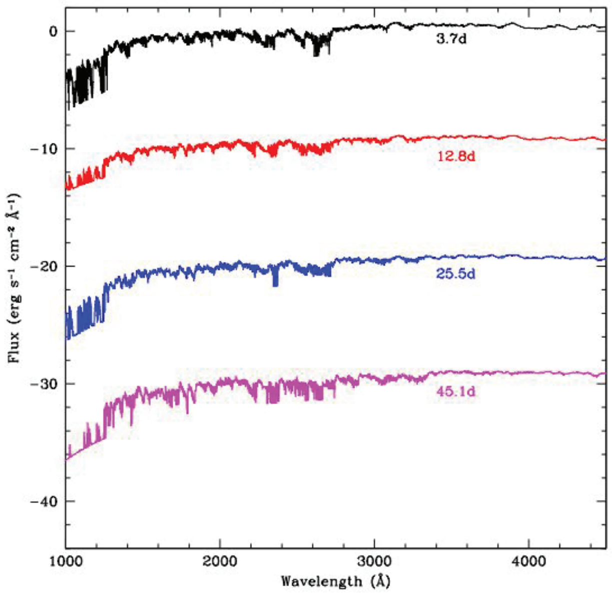

Fig. 2. Spectra (emission as a function of photon wavelength) of the explosion of a type Ib supernova at four different times. All of the structure in this plot is real, mostly due to blends of atomic lines. Here we use opacities derived by the atomic physics group at LANL.

optical bands. Currently, the state-of-the-art in calculating light curves has focused only on this source of radiation, calculating the radiation transport on homologous outflows without calculating the hydrodynamic effects. These calculations do not include any heating by shocks and can only include the mixing in supernovae through a simplified estimate.

Such simplified calculations are not valid for many supernovae. Fryer et al. [1], using the LANL RAGE code, found that for gamma ray burst (GRB)-associated supernovae, shock heating, not ^{56}Ni decay, dominates the light curve. Their discovery showed that shock heating can dominate the luminosity from supernovae blasting through large stellar envelopes (type II supernovae), strong stellar winds (type Ib/c supernovae including those associated with long-duration GRBs), or any other extended stellar environment (some supernovae Ia progenitors – e.g., [2]). To truly understand the light curves of these supernovae, the explosion must be followed using a radiation-hydrodynamics code to include shock heating. With supernova 1987A, it was also realized that mixing in the supernova, possibly enhanced by asymmetries in the explosion, is also critical to modeling accurate light curves.

The exploding star is subject to both Richtmeyer-Meshkov and Rayleigh-Taylor instabilities. The detailed mixing (Fig. 1) caused by these instabilities is crucial to understanding the emission of supernovae. Figure 1 represents the first step LANL scientists have made in better understanding this mixing. Working with scientists at the Museum of Natural History in New York, a movie of this simulation is being produced for the Hayden Planetarium. But we still have a long way to go to understand this mixing completely, and we are already planning simulations using Roadrunner.

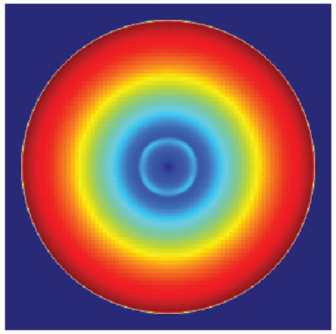

Fig. 3. Velocity plot of the first 3D radiation-hydrodynamics simulation. This simulation marks a first step in being able to model asymmetric simulations.

Figure 2 shows detailed spectra derived using the RAGE radiation-hydrodynamics code developed at LANL coupled with the detailed opacities produced by the atomic physics group at LANL. These spectra are the first produced by a radiation hydrodynamics code. But the simulation in Fig. 2 was 1D. We are now moving to 3D simulations (Fig. 3). With Roadrunner, we expect to complete full calculations in 3D next year, including studies of asymmetric supernovae.

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[1] C.L. Fryer, A.L. Hungerford, P.A. Young, *Astrophys. J.* **662,** L55 (2007).
[2] I. Hachisu, M. Kato, K. Nomoto, *Astrophys. J.* **679,** 1390 (2008).
[3] C.L. Fryer, G. Rockefeller, M.S. Warren, *Astrophys. J.* **643,** 292 (2006).

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